

II. MICROWAVE GASEOUS DISCHARGES

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A. BREAKDOWN IN HYDROGEN AT 100 MEGACYCLES

Several changes have been made in the 100-Mc reentrant cavity and the associated measuring equipment to extend the range and check the accuracy of the data obtained. The 7070 pyrex glass cylinder in the vacuum chamber was replaced by a low-loss, low temperature coefficient, dielectric ceramic cylinder (Al-200 alumina from Coors Porcelain Co.) which doubled the maximum obtainable electric field within the cavity. Because of the necessity of using high power in the region of high pressure and the resultant heating of the cavity and dielectric, a cooling coil and several blowers were added to the cavity to dissipate the heat and prevent excessive rise in the temperature of the gas sample. Since density is the real parameter involved in the experiment, pressure may be used when the density is a function of pressure only and not of temperature.

Previous measurements in the medium and high pressure ranges showed an unexplainable decreasing slope of the E vs p curve in the medium pressure range and an increasing slope in the high pressure range. Theoretical possibilities for such an occurrence were considered but further investigation suggested that the data in this region were unreliable. The Micro-match wattmeters which were used for power measure-

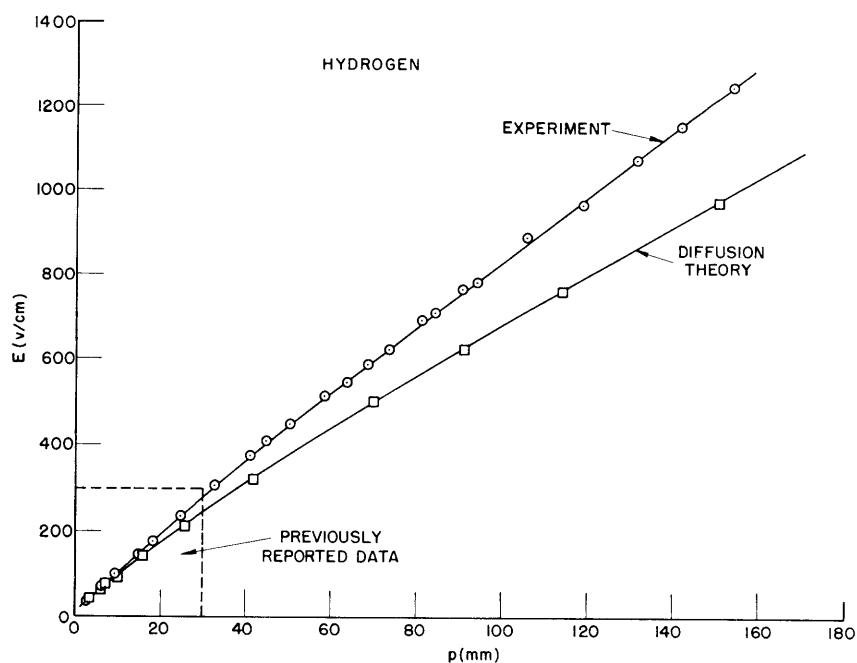


Fig. II-1 Plot of breakdown electric field vs pressure of hydrogen in 100-Mc cavity.

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ments in this experiment were checked and calibrated against the Bird Model 67 wattmeter which was used as the standard wattmeter. To get an independent check on the power readings, a GR Model 1800-A vacuum tube voltmeter was used to measure the voltage on a matched line through a specially-constructed probe adapter. Comparisons were made with previous calibrations of the Micro-match and Bird wattmeters. These showed that while the Bird wattmeter calibration was reasonably good on low-scale readings, it deviated considerably for high-scale values and in general, except for the lowest scale, the Micro-match wattmeter gave readings in good agreement with the values calculated from voltage measurements. Using this new calibration for the wattmeters, the data were corrected and the anomalous behavior of the E vs p data was removed. Further attention to details of amplifier plate tuning, cavity matching and true resonance indication resulted in the data shown on the E vs p plot of Fig. II-1.

To date the breakdown electric field has been extended to 1250 volts/cm at a pressure of nearly 155 mm of hydrogen. At low values of E and p, the data are in very good agreement with those obtainable at microwave frequencies and are consistent with the theory involving only the diffusion of electrons as the major removal process. At high pressures and high values of electric field there is disagreement between simple theory and experiment. Although the data seem quite reliable, further work is being done both in theory and in experiment to bring them into agreement or to explain their deviation.

B. THE STEADY-STATE DISCHARGE IN HYDROGEN

Methods of measuring the electric field and electron density in a steady-state microwave gas discharge have been outlined (1). The theoretical treatment of the spatial and energy distributions of electrons in such a discharge has been reported (2). The theory has now been refined somewhat, and some remarks must be made about it.

Equation 6 of reference 2 is

$$\nu_{xi} f - \frac{2m}{Mv} \frac{d}{du} (uv\nu_c f) = \frac{v}{3} \left\{ \frac{1}{u} \frac{d}{du} \frac{uv}{\nu_c} E_e^2 \frac{df}{du} - \frac{vu_s}{\nu_c \Lambda^2} \frac{df}{du} - \frac{v}{\nu_c \Lambda^2} f \right\} \quad (1)$$

where f is the electron energy distribution function, u is the energy in electron volts, v is the velocity, ν_c is the collision frequency of electrons with gas atoms, E_e is an effective field defined in reference 2, Λ is the cavity diffusion length, m/M is the electron-molecule mass ratio, ν_{xi} is the frequency of excitation and ionization as a function of u, and, finally u_s is a measure of the space charge field. The significance of these quantities is given in reference 2.

Equation 1 above can be multiplied by $4\pi v^2 dv$ and integrated from zero to infinity. The term in m/M which represents the energy loss of electrons with gas molecules drops

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out at both limits, and the remainder of the integrals may be expressed as

$$\frac{\pi}{3} \left(\frac{2e}{m} \right)^{5/2} \frac{\sqrt{u_e} \beta E_e^2}{\nu_c} = \bar{\nu}_{xi} + \frac{D - u_s \mu_-}{\Lambda^2} \quad (2)$$

where

$$u_e = \frac{2eE_e^2}{3m\nu_c^2 \sigma} \quad (3)$$

$$\sigma = \frac{2m}{M} - \frac{2eu_s}{3m(\nu_c \Lambda)^2} \quad (4)$$

$$\frac{1}{\beta^2} = 1 + \left(\frac{2u_e}{E_e \Lambda} \right)^2 \quad (5)$$

and e is the electronic charge. The left-hand side of Eq. 2 is obtained after substitution for f , reference 3, and arises from evaluation of the integral of the term containing E_e in Eq. 1, at $v = 0$. The term is $G(0)$ where, in general, $G(u)$ is the rate at which electrons cross the energy value u . $G(0)$ is not zero, for all electrons suffering inelastic collisions or produced anew through ν_{xi} have been assumed to start out at zero energy. Equation 2 thus states that the number of electrons climbing up from zero energy equals the number lost by flow out of the region (the last term on the right), plus the number lost by inelastic collisions (represented by $\bar{\nu}_{xi}$). Here

$$\bar{\nu}_{xi} = \int_0^{\infty} \nu_{xi}(u) f 4\pi v^2 dv$$

and

$$\frac{D - u_s \mu_-}{\Lambda^2} \equiv \bar{\nu}_d \quad (6)$$

is defined in reference 2.

The steady state occurs when $\bar{\nu}_d = \bar{\nu}_i$; i.e. the electrons produced by ionization just balance those lost by electron flow. Substitution of $\bar{\nu}_i$ for the last term in Eq. 2 then yields a transcendental equation in E_e/p , $p\Lambda$, and u_s which is satisfied in the steady state. In principle, the resulting equation is related to a previous steady state condition (Eq. 10, ref. 2) by integrations by parts. But the solution for f must, in practice, be solved approximately (3), so that the two methods differ slightly. It is thought that

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the present method is more reliable.

The remainder of the solution proceeds as in reference 2. An approximation may be made at high $p\Lambda$ (i. e., high pressure), which may be developed from Eq. 1. At high pressure, the terms in Λ and u_s drop out; since the only difference between breakdown and the steady state is the term u_s , all energy distributions are the same at the same E_e/p . The steady-state condition derived from Eq. 6 still holds however, and may be written

$$\frac{D}{\Lambda_e^2} = \bar{\nu}_d = \bar{\nu}_i \quad (7)$$

where

$$\Lambda^2 = \Lambda_e^2 \left(1 - \frac{u_s \mu}{D}\right) \quad (8)$$

Equation 7 is the condition for breakdown in a cavity of diffusion length Λ_e . Thus lines of constant u_s on the $(E_e/p) - p\Lambda$ plane are derived from the breakdown curve of the gas, where Λ is to be altered in accordance with Eq. 8.

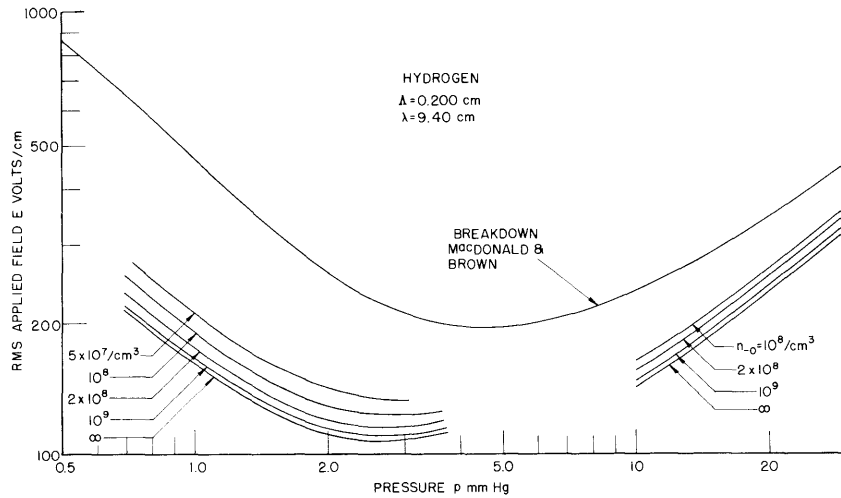


Fig. II-2 Maintaining electric field vs pressure for values of n_0 , the electron density at the center of the cavity (theoretical).

The theoretical predictions of the maintaining electric field are shown in Fig. II-2, as a function of pressure and electron density for a cavity of diffusion length $\Lambda = 0.200$ cm and a wavelength of the applied field $\lambda = 9.4$ cm. The high pressure approximation is shown at the right. Computations have not been performed for the range $4 < p < 10$ mm Hg. The experimental results are shown in Fig. II-3 for such a cavity and wavelength of applied field.

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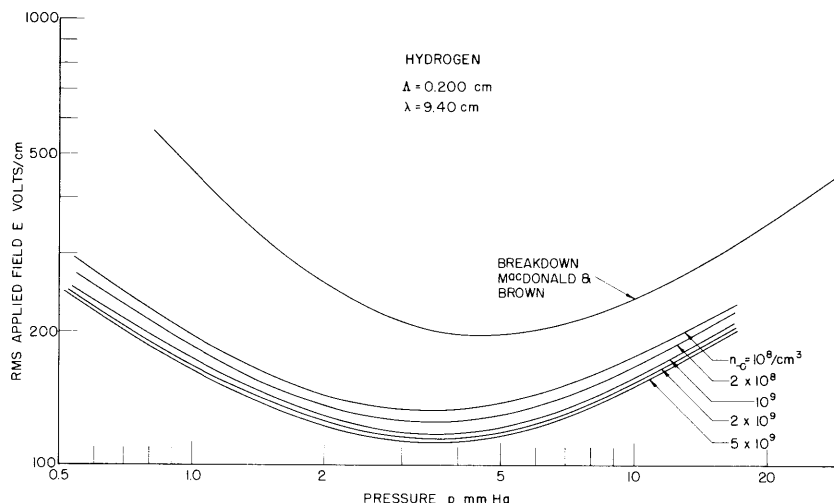


Fig. II-3 Maintaining electric field vs pressure for values of n_0 , the electron density at the center of the cavity (experimental).

The maximum discrepancy between theory and experiment is about 14 percent, which is approximately the maximum expected error of both theory and experiment combined. The rate of change of field with electron density is predicted within a factor of 1.5 in density, except very near the limit of infinite density, where the rate of change of field with density goes almost to zero. This latter discrepancy can be attributed to the presence of a space charge sheath near the walls of the discharge cavity, whose effect has been ignored in the solution of the spatial distribution of electrons.

References

1. Quarterly Progress Report, Research Laboratory of Electronics (January 15, 1950) Page 19 et seq.
2. Quarterly Progress Report, Research Laboratory of Electronics (July 15, 1950) Page 11 et seq.
3. A. D. MacDonald, S. C. Brown: Phys. Rev. 76, 1634 (1949).

C. COLLISION CROSS SECTIONS

Measurements at thermal energies (0.04 volt) of P_c , the effective area per unit volume per unit pressure normalized to 0°C for elastic collisions between electrons and molecules, have been repeated in helium and extended to include hydrogen and neon. The microwave method has been refined and recent data indicate a slightly higher mean value, $P_c = 19$, for helium than the result given in the Quarterly Progress Report, July 15, 1950. Selected averages give mean values of 47 for hydrogen and 3.4 for neon. These values should be considered as tentative figures for two reasons. First, the measured values of σ_r/σ_i , the ratio of real to imaginary parts of the complex conductivity of the ionized plasma, are used to calculate P_c by distribution theory in which it is assumed

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that P_c is independent of velocity. Second, relatively large probable errors are believed to have been present during some of the measurements, notably in helium and hydrogen. The average deviation from the mean values given above is about ± 10 per-cent.